

AEROSPACE PAYLOADS LEAK TEST METHODOLOGY

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ABSTRACT

Pressurized and sealed aerospace payloads can leak on orbit. When dealing with toxic or hazardous materials, requirements for fluid and gas leakage rates have to be properly established, and most importantly, reliably verified using the best Nondestructive Test (NDT) method available. Such verification can be implemented through application of various leak test methods that will be the subject of this paper, with a purpose to show what approach to payload leakage rate requirement verification is taken by the National Aeronautics and Space Administration (NASA). The scope of this paper will be mostly a detailed description of 14 leak test methods recommended.

KEYWORDS: leakage, leak test, payload, sensitivity, verification.

INTRODUCTION

All payloads designed to fly aboard the International Space Station (ISS) are to be evaluated by the Payload Safety Review Panel (PSRP) at Johnson Space Center (JSC) before launch to mitigate risk to the crew and station. Safety hazards that can be coupled with a payload include numerous types of hazards encompassing chemical, biological, fire, and other physical hazards.

For some payloads, especially those pressurized with gases and fluids harmful to humans, their pressure integrity (or leak tightness) becomes the most critical parameter that shall be verified with the best achievable reliability, which depends on the proper selection of pass/fail criteria in addition to the leak test method(s) used.

REQUIREMENTS FOR HAZARD CONTROL AND VERIFICATION

Safety Requirements

Adequate containment shall be provided by the use of an approved pressure vessel or the use of two or three redundantly sealed containers. Levels of containment are dependent upon the toxicological hazard for a chemical with a vapor pressure below 15 psia. The Payload Developer (PD) must ensure that each level of containment will not leak under the maximum use condition (vibration, temperature, pressure, etc.).

Documentation of chemical usage, along with the containment methods, should be supplied for review and approved by the JSC PSRP. Pressure integrity shall be verified at the system level.

Acceptance

Levels of containment must be qualified to withstand Maximum Design Pressure (MDP) with required factor of safety. Furthermore, nondestructive evaluation may be required. Details for test configuration, fluid type, environmental conditions, leak tests, functional, and acceptance tests should also be submitted for review. Qualification programs and verification data are reviewed based on risk level. The JSC PSRP acts as an auditing function, with the PD being ultimately responsible for project safety. New technology and/or unconventional controls and verifications will result in heavy scrutiny by the PSRP.

Hazard Control and Verification

Accepted controls and verifications depend upon design, application, and risk. *critical hazards* require either a Design for Minimum Risk (DFMR) approach or two levels of containment. *catastrophic hazards* require either a DFMR approach or three levels of containment. The DFMR and/or each level of containment must be verified. The DFMR for catastrophic leakage is considered fracture critical and must meet specific requirements. For pressure systems, pressure integrity must be verified at the system level.

Verification Examples

Verification examples encompass the following components:

- Review of design.
- Assessment of Hazardous Material Summary Table (HMST).

- Qualification/Acceptance (proof pressure) tests of each level of containment under worst case conditions/environment - followed by leak test.
- Acceptance leak test of each level of containment.
- Materials compatibility.
- Workmanship/Assembly inspections.
- Vibrations tests - followed by functional and leak tests.
- Certification of completed fill procedures to include proper type and quantity of fluid.

PAYLOAD PRESSURE INTEGRITY VERIFICATION

It was necessary to develop guidelines for the payload pressure integrity verification. All the known NDT methods were analyzed and JSC experts made their selections and applicability recommendations that will be discussed further. The most important part in this development process was to avoid the PDs' errors in the leak test methods application and implementation. At the same time, it was highly desirable to formulate requirements in a way for which NASA has standards.

Leak Test Methodology

Payload leak tests are considered adjunctive to payload qualification and acceptance environmental tests in that their results are part of the success criteria for these tests. Tab. 1 shows methods which are described further in the Recommended Leak Test Methods section of this paper.

Table 1: Leak Test Methods and Leakage Rates That Could Be Reliably Verified

Method No.	Leak Test Method	Leakage Rate That Could Be Reliably Verified (sccs)
Methods for Total Internal-to-External Leakage Rate Verification		
I	Vacuum Chamber	1.0E-09
II	Accumulation	1.0E-07
IIIa	Pressure Change [Pressure Decay Technique]	1.0E-04
IV	Mass Loss After Vacuum Exposure	5.0E-05
Methods for Total External-to-Internal Leakage Rate Verification		
IIIb	Pressure Change [Pressure Rise Technique]	1.0E-05
V	Hood	1.0E-09
Methods for Total Internal-to-Internal Leakage Rate Verification		
VI	Volumetric Displacement	1.0E-03
VII	Leak Detector Direct Connection	1.0E-08
Methods for Local Internal-to-External Leakage Rate Verification		
VIII	Immersion	1.0E-04
IX	Chemical Indicator	5.0E-06
X	Detector Probe	1.0E-05
XI	Local Vacuum Chamber	5.0E-10
XII	Foam/Liquid Application	1.0E-04
XIII	Hydrostatic/Visual Inspection	1.0E-04
Methods for Local External-to-Internal Leakage Rate Verification		
XIV	Tracer Probe	5.0E-08

Test methods, other than those identified herein, should be presented in enough detail to allow the PSRP to review and arrive at the same conclusion as the PD. That is, the test methods possess necessary sensitivity, calibration, appropriate time duration, test setup, and qualified test personnel to ascertain that the leakage rates defined can be accurately verified. The PSRP will examine this methodology on a case-by-case basis.

In one unique case where a payload contained a highly caustic, hazardous material, the PD stated the intent was to submerge the payload in water and measure the pH of the water over an extended period of time for any change. The sensitivity of the measuring device was capable of detecting very minute changes in the water pH. This method was deemed acceptable by the PSRP after calculations confirmed that the required maximum allowable leakage rate could be verified using this test methodology proposed by the PD.

Generally, methods other than those for total internal-to-external (for pressurized payloads) and external-to-internal (for sealed payloads) leakage rate verification should not be used for payload pressure integrity verification without special justification.

The leak test method employed must have sensitivity and accuracy consistent with the specified maximum allowable leakage rate. Specifically, the method should be checked to have the sensitivity to detect leakage rate of at least half of the specified maximum allowable leakage rate. For example, if the maximum allowable leakage rate is less than 1.0E-04 sccs, the method ("end-to-end" test setup) used should be demonstrated by use of a standard leak source to be capable of detecting at least 5.0E-05 sccs. This sensitivity check should be performed before every leak test. Also, local leak detection methods, e.g., Detector Probe, should not be used to verify requirements for total leakage rate for a payload. Payload leakage rate specifications are determined based on standard methods derived for the seal design.

If the payload has redundant seals, seal pressure integrity should each be verified independently. One of the possible ways to do verification is to use the very first portion of the test (e.g., the first 30 - 120 seconds depending on seal design, its material, and size) to check whether the mass spectrometer leak detector response is greater than 1.0E-07 sccs of Helium.

Leak testing may be performed prior to payload proof pressure testing in lieu of post proof pressure testing only if approved by the responsible safety organization. In all cases, leak testing must be conducted after the payload proof pressure test if they are not performed together.

When temperature potentially affects the sealing materials or surfaces, an evaluation of hardware design and operational characteristics should be performed, and if technically warranted, the leak test should be conducted at the minimum and maximum qualification temperature limits. A leak test at temperature limits is warranted on a payload of a given level-of-assembly due solely to one or more lower tier payloads comprising the assembly, and if it can be shown that all of those lower tier payloads receive an appropriate leak test at temperature limits as part of a lower level qualification test, then the higher level-of-assembly does not require leak testing at temperature limits.

Applicable safety standards should be followed in conducting all tests. Any fluids used for leak testing should be compatible with operational media. Helium mass spectrometer or other leak detectors may be used for detecting leakage rates starting from 1.0E-09 sccs and higher. Leak detection and measurement procedures may require vacuum chambers, bagging of the entire payload, or other special techniques to achieve the required accuracy. The selected method should be included in the Payload Verification Plan coordinated with the responsible authority.

The following test methods are recommended for *pressurized payloads*: Methods I, II, IIIa, VI, VII, VIII, IX, X, XI, XII, or XIII as appropriate. The following test methods are recommended for *sealed payloads*: Methods IIIb, IV, V, or XIV as appropriate.

Maximum Allowable Leakage Rates

Tab. 2 shows recommended maximum allowable leakage rates and leak test methods that should be employed to verify the pressure integrity.

Table 2 Recommended Maximum Allowable Leakage Rates and Leak Test Methods to Verify Pressure Integrity and Pinpoint Local Leaks

Toxicity Level or Other Limitations	Maximum Allowable Leakage Rate to Be Verified: Test Methods
catastrophic	No greater than 1.0E-09 sccs : <ul style="list-style-type: none"> • Method I (to verify pressure integrity) • Methods X, XI, and XIV (to pinpoint local leaks)
critical	No greater than 1.0E-07 sccs : <ul style="list-style-type: none"> • Methods I and II (to verify pressure integrity) • Methods X, XI, and XIV (to pinpoint local leaks)
Fluid (gas or liquid) leak is not allowed or desired	No greater than 1.0E-04 sccs : <ul style="list-style-type: none"> • Methods I, II, III, and IV (to verify pressure integrity) • Methods VIII through (to pinpoint local leaks)

General concerns about leaks unrelated to safety	No greater than 1.0E-03 sccs: Methods I through XIV (to verify pressure integrity and/or pinpoint local leaks) depending on flow direction through leaks (out of or into payload)
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Recommended Leak Test Methods

The following sections describe in greater detail the characteristics of the 14 recommended leak test methods listed in Tab. 1.

Method I (Vacuum Chamber)

This method may be used for total internal-to-external leak testing of pressurized payloads. The payload shall be completely placed in a vacuum chamber (bell jar) and tested for total leakage with a leak detector appropriate for the tracer gas used. The leak test setup (a vacuum chamber or bell jar and a leak detector) calibration shall be performed with the standard leak that shall be quantitatively less than the minimum leakage rate to be detected by a factor of at least two to ensure reliability of measurements. After calibration is done, the leak test setup relative sensitivity shall be determined and used to calculate the payload leakage rate. The payload shall be charged with a known concentration of the tracer gas to the required pressure. Pressure shall be maintained until stabilization of the leak detector output is achieved (stabilization shall be defined as four consecutive readings no less than five minutes apart with no more than a 10 percent variation in the leak detector output from one measurement to the next, including the first and last measurements; if the leak detector outputs are decreasing or fluctuating rather than steadily increasing, stabilization requirement is not applicable). Calibration data and leak detector initial and final readings shall be recorded. The final payload leakage rate shall be recorded along with four data points within 15 minutes duration to demonstrate stabilization in accordance with the definition above. Note that the requirements for:

- Standard leak selection,
- Leak test setup calibration,
- Leak test setup sensitivity to be used for the payload leakage rate calculation,
- Payload to be charged with a known concentration of the tracer gas to the required pressure,
- Leak detector output stabilization, and
- Calibration data and final payload leakage rate recording

are the same for all the leak test methods that employ Helium as a tracer gas and thus not repeated hereinafter.

Method II (Accumulation)

This method may be used for total internal-to-external leak testing of pressurized payloads. The payload shall be enclosed in a suitable enclosure. The standard leak shall be placed in the enclosure for a predetermined period of time. At the end of the time period, a detector probe shall be placed in the enclosure and the maximum leak detector response shall be recorded. The enclosure shall then be purged with nitrogen or air. The payload shall be charged with a known concentration of the tracer gas to the required pressure. Prior to examination, the test pressure shall be held for a minimum duration of 30 minutes for joints with seals and of five minutes for welds and fittings or plugs with no seal. The enclosure shall be purged with nitrogen or air until the tracer gas background inside it is equal to or less than the tracer gas concentration in the test facility and sealed. After the time period used for the calibration, the detector probe shall be placed in the enclosure.

Method III (Pressure Change)

This method is implemented either as a pressure decay or a pressure rise technique depending upon the applications. The pressure decay technique (IIIa) may be used for total internal-to-external leak testing of pressurized payloads. To improve the accuracy of this technique, a reference vessel connected to the pressurized payload may be used. If ambient temperature changes, the payload and reference vessel volumetric changes shall be taken into account. The pressure rise technique (IIIb) may be used for total external-to-internal leak testing of sealed payloads. The payload internal pressure, barometric pressure, and ambient temperature (or temperature of the payload) shall be monitored for the required time to determine the actual pressure drop or rise and the corresponding leakage rate. The pressure gauge/transducer shall have accuracy adequate to measure the minimum required pressure change. The tolerance/error associated with the total internal volume of the payload and test fixture under pressure used for the leakage rate calculation shall be taken into account as a maximum positive value.

Method IV (Mass Loss After Vacuum Exposure)

This method may be used for total internal-to-external leak testing of fluid-filled payloads such as batteries. The payload shall be weighed before and after the test and “no leakage” shall be confirmed by its mass loss or leakage rate recalculated based on a mass loss. The payload shall be completely placed in a vacuum chamber (bell jar) and exposed to vacuum to verify that it has no seal problem. For some fluids such as alkaline electrolyte, an additional check per Method IX shall be done to verify that there are no local leaks.

Method V (Hood)

This method may be used for total external-to-internal leak testing of sealed payloads. The payload internal volume shall be evacuated to a vacuum compatible with the tracer gas leak detector. The standard leak shall be installed at the furthest possible point from the leak detector. For the payloads that have only one leak test port, the standard leak shall be installed at this port. The external surfaces of the payload shall be exposed to a verified concentration of a tracer gas.

Method VI (Volumetric Displacement)

This method may be used for total internal-to-internal leak testing of pressurized payloads such as valves, pressure regulators, or heat exchangers. One side of the payload shall be pressurized to the required pressure while the other side across the internal barrier shall be sealed from the atmosphere and attached to a suitable device for the purposes of demonstrating volumetric displacement. This will be accomplished by either using a displacement of liquid or by moving a fluid meniscus along the graduations of the measuring device.

Method VII (Leak Detector Direct Connection)

This method may be used for total internal-to-internal leak testing of pressurized payloads such as valves, pressure regulators, or heat exchangers. The standard leak shall be installed at the furthest possible point from the leak detector. One side of the payload shall be charged with a known concentration of the tracer gas to the required pressure while the other side across the internal barrier shall be sealed from the atmosphere and attached to the leak detector.

Method VIII (Immersion)

This method is a semi-quantitative technique that may be used to detect and locate internal-to-external leaks in pressurized payloads and shall be used only as a pass/fail test (welds, fittings, and plugs) or for troubleshooting purposes. Internal gas pressure shall be applied across the pressure boundary for a minimum duration of 15 minutes before the test liquid contacts the external surface. Lighting in the area to be examined shall be no less than 1000 lux or lumen/m² (100 foot-candles) in brightness. Illumination shall be free from shadows over the surface area under inspection. The observer shall place his/her eyes within 60 cm (2 feet) of the surface to be examined. Mirrors or magnifying glasses may be used to improve visibility of indications. The payload shall be completely immersed in a liquid. The critical side or sides of interest of the payload shall be in a horizontal plane facing up. There shall be no observed leakage during immersion (as evidenced by one or more bubbles emanating from the payload that are in diameter at least 3 times bigger than so called *champagne* bubbles that could be a reason of a test gas permeation through the test article such as Teflon flex hose).

Method IX (Chemical Indicator)

This method may be used for local internal-to-external leak testing of pressurized payloads. This method shall be used only as a pass/fail test; this method does not provide a quantitative measurement of payload leakage rate and should not be used for verifying the total leakage rate requirement. A suitable indicator such as a dilute solution of phenolphthalein or other suitable color-change indicator such as colorimetric shall be applied to all seams, terminals, and pinch tubes subject to leakage of the working fluid. A change in the color of the indicator shall be an indication of a leak. After testing, the indicator shall be removed (for example, with distilled water).

Method X (Detector Probe)

This method is a semi-quantitative technique that may be used to detect and locate internal-to-external leaks in pressurized payloads and shall be used only as a pass/fail test (welds, fittings, and plugs) or for troubleshooting purposes. Prior to examination, the test pressure shall be held for a minimum duration of 30 minutes for joints with seals and of five minutes for welds and fittings or plugs with no seal. Prior to examination, the tracer gas background shall be measured and the leak test setup (a detector probe attached to a leak detector) calibration shall be performed by passing the detector probe tip across the orifice of a standard leak. The resulting leak detector output shall be at least 40 percent above the tracer gas background. After the calibration, the detector probe tip shall be passed over the test surface at the same scanning rate and distance used during the system

calibration. The leak test setup calibration shall be repeated every 60 minutes, anytime test conductors/operators are changed, and after the test. Any leak detector output above the established tracer gas background with allowance made for atmospheric tracer gas variations and leak detector drift, that in the aggregate do not exceed 40 percent of the tracer gas background, indicates a leak.

Method XI (Local Vacuum Chamber)

This method may be used for local internal-to-external leak testing of pressurized payloads and should not be used for verifying the total leakage rate requirement. The local vacuum chamber or bell jar connected to the tracer gas leak detector shall be installed on the payload area to undergo the leak test.

Method XII (Foam/Liquid Application)

This method is a semi-quantitative technique that may be used to detect and locate internal-to-external leaks in pressurized payloads and shall be used only as a pass/fail test (welds, fittings, and plugs) or for troubleshooting purposes. The payload internal and external surfaces shall be cleaned and dried to remove any liquid and moisture from leakage paths. Specially formulated bubble-forming solutions shall be prepared accordingly to existing standards. The payload shall be pressurized to maximum design pressure with test gas (for example, oxygen for oxygen payloads; air or nitrogen for non-oxygen payloads) for greater than 10 minutes before applying bubble-forming solution, to prevent clogging of small leaks. The bubble-forming solution shall be applied to the low-pressure side of the payload, such that the payload test areas are completely covered with a blanket of bubble forming solution (three to seven mm for foam application or uniformly for liquid application). The payload shall be inspected for bubbles, using a lamp and hinged mirror to check hard-to-observe areas. Leakage is identified by detection of bubbles being formed by test gas flowing through the bubble-forming solution. Any detected bubble or bubbles constitute failure of the payload. After completion of test the payload shall be cleaned and cleanliness inspected.

Method XIII (Hydrostatic/Visual Inspection)

This method is a semi-quantitative technique that may be used to detect and locate internal-to-external leaks in pressurized payloads and shall be used only as a pass/fail test (welds, fittings, and plugs) or for troubleshooting purposes. The payload external surfaces shall be cleaned and dried to remove any liquid and moisture from leakage paths. Any appropriate test fluid compatible with the payload to be tested shall be used. The payload shall be pressurized to the required pressure with test fluid (for example, deionized or distilled water with or without visibility enhancer and/or additive to lower a resistance to flow such as fluorescent dye tracer, added, coolant for thermal control system payloads, etc.). Lighting in the area to be examined shall be no less than 1000 lux or lumen/m² (100 foot-candles) in brightness. Illumination shall be free from shadows over the surface area under inspection. The observer shall place his/her eyes within 60 cm (2 feet) of the surface to be examined. The payload's leak paths shall be visually inspected for an absence of test fluid droplets every thirty minutes during the test using a lamp and hinged mirror to check hard-to-observe areas. Also absorbent wipes, blotting paper, or other products such as water developer that changes color in contact with moisture shall be used to enhance a visibility of leaking test fluid. There shall be no observed leakage as evidenced by one or more test fluid droplet of any diameter.

Method XIV (Tracer Probe)

This method may be used to locate known external-to-internal leaks but should not be used for verifying the total leakage rate requirement. The payload internal volume is evacuated to a vacuum compatible with the tracer gas leak detector. The tracer probe is connected to a source of 100 percent tracer gas with a valved opening at the other end for directing a stream of tracer gas over the payload. Any indication of tracer gas above the background by the leak detector indicates a leak.

Test Levels, Duration, and Supplementary Information

The leak tests should be performed with the payload pressurized at the MDP and then at the minimum design pressure if the seals are dependent upon pressure for proper sealing. Regardless of the method used, the test duration should be sufficient to detect any out-of-specification leakage.

Rationale used in determination of leakage rates specified in these guidelines encompasses the following:

- Largest leakage rate is for non-safety containment leak testing that should allow the simple, less expensive, and most commonly used leak test methods such as Pressure Change/Pressure Decay Technique (for total internal-to-external leakage rate verification), Foam/Liquid Application and Immersion (for local internal-to-external leakage rate verification or pinpointing local leaks).

- Generally accepted leak test sensitivity without any special care given (no smaller leakage rate can be indicated by these methods) is in the range of $1.0\text{E-}04$ – $3.0\text{E-}04$ sccs. If no gas leak is indicated with these methods, there will not be any immediate, obviously noticeable, indications of a liquid leak.
- With more intensity (such as longer duration, best lighting, and higher pressure) the sensitivity of these methods can be improved.
- Leaks resulting in critical and catastrophic hazards, as indicated by toxicity, biological assessment, flammability, interference with environmental control life support system, loss of required service, and the DFMR (fracture critical) failure requires better leak test sensitivity than can be provided by the simple, inexpensive methods used for non-safety leak testing.
- Tracer gas (largely Helium) mass spectrometer leak detector is the most commonly used sensitive leak test equipment.
- By specifying a maximum allowable leakage rate of $1.0\text{E-}07$ sccs, a tracer gas mass spectrometer leak detector or leak test equipment with comparable sensitivity will be required for leak testing for leaks that can cause a critical hazard.
- Because of the many erroneous "no-leak" indications that can be obtained, more rigorous attention must be given to test equipment calibration and operator certification for tracer gas mass spectrometer leak detector testing.
- Leaks that can cause catastrophic hazards require the most sensitive, demanding tracer gas mass spectrometer leak detector testing using a vacuum chamber (bell jar) to verify the leak test requirement of $1.0\text{E-}09$ sccs. This required leak test setup sensitivity should be limited to only cases where it is essential to verify the flawless containment integrity and leakage rate quantification.

CONCLUSIONS

Payloads' pressure integrity is critically important. NDT experts are continuously working to improve existing as well as to develop new reliable leak test methodology. The strong cooperation between NDT, safety, and payload communities should be maintained to ensure successful future spacecraft endeavours.

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REFERENCES

1. Jackson, Charles N., et al., *Nondestructive Testing Handbook*, Third edition: Volume 1, *Leak Testing*, American Society for Nondestructive Testing, 1997.
2. SSP 57020, *Pressurized Payload Accommodation Handbook*, 2004.
3. NASA-STD-7002A, *Payload Test Requirements*, 2004.
4. NASA-HDBK-5010, *Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware*, 2005.
5. NASA-STD-5009, *Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components*, 2008.
6. ASTM E 432, *Standard Guide for Selection of a Leak Testing Method*, 1997.
7. ASTM E 493, *Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode*, 1997.
8. ASTM E 498, *Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Tracer Probe Mode*, 2000.
9. ASTM E 499, *Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Detector Probe Mode*, 2000.
10. ASTM E 1003, *Standard Test Method for Hydrostatic Leak Testing*, 2005.
11. ASTM E 1066, *Standard Test Method for Ammonia Colorimetric Leak Testing*, 2000.
12. ASTM E 1603, *Standard Test Methods for Leakage Measurement Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Hood Mode*, 1999.